

# Vehicular Energy Network

Albert Y.S. Lam, Ka-Cheong Leung, and Victor O.K. Li

**Abstract**—The smart grid nurtures many innovative ideas and applications, and it revolutionizes the power system. Unfortunately, many of these new ideas cannot be easily integrated into the existing power system due to power reliability and security reasons. We can build an energy transmission system upon the traffic network and utilize electric vehicles (EVs) as energy carriers to transport energy over a large geographical region. We construct a generalized architecture called the vehicular energy network (VEN) and develop a mathematically tractable framework for VEN. Dynamic wireless (dis)charging allows electric energy, as an energy packet, to be added and subtracted from EV batteries seamlessly. With proper routing, we can transport energy from the sources to destinations through EVs along appropriate vehicular routes based on the information via the vehicular ad-hoc network. This paper gives a thorough preliminary study of VEN with characteristics listed and possible drawbacks discussed. We illustrate its significance by setting up a VEN with real traffic data in the United Kingdom. Our implementation shows that a substantial amount of renewable energy can be transported from some remote wind farms to London under some reasonable settings. VEN can complement the power network and enhance the overall power transmission rate. With packet switching-like design, many further developments can be built upon VEN by incorporating ideas and results from the data networking domain.

**Index Terms**—Dynamic charging, electric vehicle, energy routing, energy transmission.

## I. INTRODUCTION

The smart grid potentially revolutionizes the power system by incorporating many new components, such as renewable energy, demand response, smart meters, smart appliances, electric vehicles (EVs), and energy storage. There have been plenty of smart grid projects, spawning many brilliant ideas. Many of them can produce excellent results, but most of them have not been implemented due to power reliability and security reasons. Any new smart grid design needs to be thoroughly tested and demonstrated to be fool-proof before being integrated into the real power system. Below we give some examples of complications when implementing new smart grid ideas:

1) *Renewable Energy*: There is tremendous amount of renewable energy generation but only a small portion is available and utilized at the loads. As of 2009, China had less than one-third of wind farms connected to the grid due to the difficulty of intermittent power dispatch and transmission network limitations [1]. In 2013, the ISO New England cut back power from wind and hydroelectric plants a few times because too much electricity was produced and transmission lines with

robust carrying capacity to connect the wind farms located in remote areas were missing [2]. Similar situations were reported in the German grid [3]. However, cutting renewable output may fail the mandates of having a certain percentage of renewable energy in the total electricity generation in some countries [4].

2) *Ancillary Services*: Power supply and demand need to be balanced at all times in order to make the system stable. When discrepancies occur between supply and demand, ancillary services, which can be achieved by reserve generators [5] or by aggregations of EVs [6], are required. Operating reserves can be provided in diverse locations of the grid and distributed energy resources (DERs), like the renewables, may be preferable over conventional generators in some situations. Further study is still required before DERs may be brought into the power system effectively.

3) *New Energy Markets*: In the power system, the demand is connected with the supply through the power (transmission and distribution) networks. The power infrastructure is generally managed or owned by a few parties. However, the smart grid can introduce many variations and uncertainties to both supply and demand, e.g., from DERs and demand responses. These new players have great potential to conceive new energy markets with non-standard operational models, but they still rely on the power network to transmit power. For example, energy trading can be set up through a vehicle-to-grid system [7]. The grid operators are responsible for the proper operation of the system. Since the power network is not open, the operators in general oppose the integration of new operational models until they have undergone the reliability and security assurance. If we can bypass the power network for energy transfer, we can help the new energy businesses thrive.

The common among the above scenarios is that the integration of new smart grid elements cannot guarantee that the operations of the current power system will not be affected. If there exists an infrastructure independent of the conventional power network to connect the various (stable or unstable) types of power sources and loads, many of the brilliant ideas in smart grid can become a reality overnight.

In [8], the idea of utilizing EVs for energy transmission and distribution was proposed and the system was called the EV energy network (or the mobile electrical grid [9]). It is assumed that there are some energy routers in a transport network, in which EVs charge up when they stop at some energy routers and discharge the energy when stopping at other energy routers. Ref. [8] focused on studying the energy router placement. In [10], a greedy algorithm for energy scheduling and allocation in the EV energy network was developed. Under a simplified setup (e.g., without considering energy transmission rate and the allowed time window for energy

A.Y.S. Lam is with the Department of Computer Science, Hong Kong Baptist University, Kowloon Tong, Hong Kong (e-mail: albertlam@ieee.org).

K.-C. Leung and V.O.K. Li are with the Department of Electric and Electronic Engineering, The University of Hong Kong, Pokfulam Road, Hong Kong (e-mail: {kcleung, vli}@eee.hku.hk).

transmission), it tried to establish energy paths connecting the energy sources and destinations without performance guarantee. Ref. [11] was dedicated to studying the impact of traffic congestion and it proposed two algorithms to simulate the traffic congestion, instead of re-configuring the energy network to combat the congestion. With the simplified settings as in [10], shortest energy routes were determined in [9]. Similarly, [12] considered multiple routes when one route was not sufficient. All these efforts are based on the model developed in [8] but lack a well-defined framework for more in-depth analysis.

In this paper, we aim to develop a framework to model an energy transmission system for transporting energy from one place to another by means of EVs. Our framework generalizes the above mentioned infrastructure and we categorize the system modeled by this framework the vehicular energy network (VEN). This framework defines the necessary components to facilitate more in-depth research. We highlight the key differences between this work and the EV energy network discussed in [8], [9], [10], [11], [12], as follows:

- We incorporate dynamic (dis)charging in the design (more details can be found in Section II) such that wireless energy transfer is possible. In this way, EVs do not need to stop at particular locations for energy charging and discharging. This can not only improve the system efficiency (as everything happens on the move), but also provide stronger incentive to largely increase the scope of participating EVs (not restricted to public transport with fixed routes);
- We quantitatively define energy “packet size” and we will show that a very small amount of energy transferred in each charging or discharging process is sufficient to result in a significantly large quantity of energy transported from the source to the destination;
- Our system is capable of selecting appropriate EVs in vehicular flows to carry energy in order to fulfill various system objectives. We do not require the EVs to actively participate in the energy transfer but the system can control the energy transfer rates over the energy paths. In other words, with appropriate control, VEN can adapt to the passive EV flows instead of controlling the routes of EVs to meet the system performance;
- Our system allows us to model the impact of vehicular routing information on system performance. With vehicular ad-hoc network (VANET), we can obtain different levels of vehicular routing information, which can be used to construct energy paths;
- We define all the necessary variables in the framework quantitatively, e.g., vehicular flow, energy packet size, energy transfer rate, transfer time window, and their relationships. These allow us to analyze the system systematically, e.g., through optimization, and develop mathematically tractable solutions.

The rest of the paper is organized as follows. We define VEN with supporting arguments, characteristics, and possible criticisms in Section II. Section III gives the system model and quantifies the transferable energy and loss. In Section IV, we

formulate the optimization problems for maximizing energy transfer and for minimizing energy loss, and give analytical results based on the two problems. Section V studies the performance of the system with real traffic data. We provide some potential extensions in Section VI and conclude in Section VII.

## II. VEHICULAR ENERGY NETWORK

### A. Supporting Technologies

1) *Renewable Energy*: To confront global warming and climate change, many nations have established targets and mandates for renewable energy use [13]. For example, various states in the United States (U.S.) have mandated renewable targets, namely, 33% and 30% by 2020 in California and Colorado, respectively. The European Union 2030 target is at least 30% of energy coming from renewable sources [13]. China sets the 15% renewable target with 500 GW renewable electricity by 2020 [13]. Moreover, renewable power capacity is massive [14]. Therefore, an appropriate approach to manage the abundant renewable energy generation can help meet various nations’ energy mandates.

2) *Electric Vehicles*: EVs refer to a family of vehicles with batteries equipped to store energy for operations, and the batteries need not be the sole sources of energy. We can consider an EV as a *movable energy storage*. For instance, we can utilize EVs as energy buffers to support regulation-up and -down services [6]. Boosting the number of EVs is also included in the green policies of many countries. For example, the U.S. sets the goal of having one million EVs on the road by 2015 [15] and China targets to have a similar goal [16]. Many automotive companies have already included EVs in their major production lines, e.g., [17], [18], [19], [20], [21], [22]. As the related equipment (e.g., batteries) is improved and the facilitates (e.g., charging stations [23]) become available, EVs will be very prevalent in the near future.

3) *Vehicular Ad-hoc Network (VANET)*: VANET is a mature technology allowing vehicles, as mobile nodes, to communicate with each other or some fixed infrastructures [24]. VANET enhances the communication capacity of the vehicles resulting in an intelligent transportation system. Newly designed vehicles, especially EVs, are equipped with many sensors and this allows VANET to support a variety of functions, such as infotainment, surveillance, and route planning. This nurtures new applications where vehicles submit (parts of) their intending traveling paths for some planning purposes.

4) *Wireless Power Transfer*: Power can be transferred over an air gap by means of inductive charging and magnetic resonance [25]. Batteries of EVs can be charged wirelessly on the move and this is called dynamic charging. Dynamic charging allows EVs to be charged more frequently so that the batteries can be made smaller and the overhead costs due to batteries can be lowered. These encourage higher sales of EVs. Some companies, like Qualcomm [26] and ABB [27], are working toward improving the wireless charging technologies for EVs. KAIST demonstrated dynamic charging prototypes in buses [28]. A Stanford team proved that power could be transferred effectively up to 10 kW with a moving car [29].

These evidences show that wireless charging and discharging can take place without interfering the movements of EVs.

### B. Description

The aforementioned technologies and developments make VEN a possible energy infrastructure. We can utilize EVs as *energy carriers*. Consider an EV moving on a particular route connecting Locations A and B. If we wirelessly charge the EV at A and discharge it at B, we bring energy from A to B via the EV. Again, suppose that after a while, another EV passes through Location B moving toward Location C. We can then charge and discharge that EV at B and C, respectively, and this allows us to bring the energy to Location C. In this way, if there are vehicular routes intersecting one another and some pass through the energy sources and destinations, we can transmit the required energy from the sources to the destinations through VEN. We formally define VEN as follows:

**Definition 1** (Vehicular Energy Network). *VEN is a vehicular network aiming to transmit energy from one place to another by means of EVs. It is built upon a road network where EVs run on certain routes and there are dynamic (dis)charging facilities, with limited storage for energy between each charge and discharge, installed at the road junctions. Nodes with energy to be delivered and received are denoted as the energy sources and destinations, respectively. During charging, a certain portion of energy is transmitted to an EV from a charging facility, and similarly, a portion of energy is transmitted from an EV to a discharging facility during discharging. An EV carries a “packet” of energy along its route between its charge and discharge. By properly charging and discharging certain EVs at particular junctions, we can bring energy from the energy sources to the energy destinations.*

Note that we do not need to actively control the EVs participating in VEN. We do not require the EVs to stop or slow down for (dis)charging at particular locations as energy can be transmitted silently at the road junctions while they are moving. We do not need the EVs to follow any dedicated routes. Instead, we select those EVs with favorable routes to carry energy so as to perform energy transmission.

### C. Characteristics

VEN possesses the following characteristics which make it suitable as a supplement to the power grid to deliver power:

1) *Controllable power transmission rate*: Energy is transmitted in the form of packets and this allows VEN to be managed like a packet-switched data network. Given the intended route of an EV, we know where the energy it carries can be delivered. By controlling how many EVs are utilized to carry energy, we can specify the energy transmission rate on each road segment.

2) *High flexibility*: We do not need to build a dedicated infrastructure in order to realize VEN. VEN relies on the existing road network, which covers almost all locations involved in civilized human activities. A road network can be transformed into a VEN when a certain number of (dis)charging facilities

have been installed. Unlike the conventional power network where the power sources and loads are generally pre-specified, the locations of energy sources and destinations on VEN can be modified from time to time.

3) *Low capital cost*: Most equipment required to build VEN is ready. EVs have become more popular and will take a dominant role in the future transportation system. Wireless electricity transfer technologies have been industrialized and dynamic charging has been researched to enhance the efficiency of EV utilization. It is expected that there will be wireless chargers set up at road segments and the future EVs will support wireless energy transfer. We can just utilize the dynamic charging equipment which is primarily installed for EV charging purposes to establish VEN. In Section V, we will show that only a small portion of supporting EVs is required for a substantial quantity of energy transmission over VEN. Therefore, a practical VEN does not require a tremendous number of participating EVs to function.

### D. Discussions

Existing technologies render VEN feasible. Here, we discuss some non-technological factors which may be important when we bring VEN into reality.

Incentives may be the most critical factor. Why would EVs participate in VEN? EV owners may be concerned about the well-being of their EV batteries, especially since the charging-discharging cycles may reduce battery lives. Incentives need to be strong enough so as to attract a sufficient number of EVs to participate in the scheme. In fact, there are some possible options. We can supply *free* energy to the participating EVs. In each charging-discharging cycle, an EV can keep some of the energy transmitted from the charging facility for its own use. As energy production from the renewable is tremendous and may be considered free,<sup>1</sup> it is possible to sustain the daily energy consumption of all participating EVs without any payment for energy if the EVs move within the service area, e.g., the whole country. Moreover, we may install a secondary (small in size) battery in each participating EV dedicated to carrying energy in VEN.<sup>2</sup> In this way, such charging and discharging will not hurt the primary batteries, which are the main energy storage for supporting the normal operations of the EVs.

EVs consume energy to move around. If there is only one single servicing battery installed in an EV, the EV will consume part of the energy dedicated to VEN. In this case, the amount of energy available to the energy destinations will be largely reduced. However, this will not be a problem if the packet size (amount of energy involved in each charging-discharging cycle) is small relative to the battery capacity. Moreover, it is no longer a concern when the EV is equipped with a secondary battery. We will study the impact of various packet sizes in Section V.

<sup>1</sup>Capturing renewable energy from nature does incur some capital costs for equipment installation and operational costs. However, they are negligible when the production is large enough for long enough period of time.

<sup>2</sup>Note that installation of small battery is not necessary but a possible artifice to realize VEN. Only vehicles equipped with batteries are required.

How many (dis)charging facilities are required to set up VEN? The more facilities, the more flexible and efficient the system is, as more energy paths (discussed in Section III) can be constructed and it will be easier to find a way to deliver energy from the sources to the destinations. We will model VEN as a graph (explained in Section III). We only need to consider those road junctions with facilities equipped as the nodes in the model. All results can be carried through with different number of facilities.

The system can work properly provided that there is a sufficient number of participating EVs. The system operator may first cooperate with public transports, e.g., electric buses and taxis, and then extend to individual private EVs. The considerable quantities of public transport vehicles and also the fixed routes and schedules of some public transports provide a certain level of energy delivery guarantee.

Last but not least, VEN will be worth further development if the total amount of energy transmitted in a reasonable time is significant. Each charging-discharging cycle incurs energy loss. The amount of energy loss should also be examined. We will study these issues in Section V with real traffic data under some reasonable assumptions.

### III. SYSTEM MODEL

#### A. Network

We model a road network with a directed graph  $\mathcal{G}(\mathcal{N}, \mathcal{A})$ , where  $\mathcal{N}$  and  $\mathcal{A}$  are the set of energy points and the set of roads connecting the energy points, respectively.  $\mathcal{N}$  includes all possible energy sources, destinations, and routing points set up at the road junctions. Let  $head(a_i)$  and  $tail(a_i)$  be the head and tail of arc  $a_i \in \mathcal{A}$ . Each arc  $a_i$  incurs a delay  $d(a_i)$  time units for transferring energy from  $tail(a_i)$  to  $head(a_i)$ ; when energy is carried by a vehicle, it takes  $d(a_i)$  units to traverse  $a_i$ . For simplicity, we assume that  $d(a_i)$ , for all  $a_i$ , are constants.<sup>3</sup>

#### B. Vehicular Traffic

Assume that the traffic flows are static. Let  $\mathcal{R}$  be the set of all possible vehicular routes in  $\mathcal{G}$ , each of which is loop-free. Each  $r_i \in \mathcal{R}$  is a sequence of connected arcs, i.e.,  $r_i = \langle a'_1, \dots, a'_{|r_i|} \rangle$  with traffic flow  $f_i$ , which is the number of vehicles traveling on  $r_i$  per unit time. We denote the  $n$ -th arc of  $r_i$  by  $r_i(n)$ . Let  $r_i(n, m)$ ,  $n < m$ , be the sub-route of  $r_i$  starting from the  $n$ -th arc and ending with the  $m$ -th arc.

#### C. Energy Path

**Definition 2** (Energy Path). *An energy path  $p(s, t)$  is the path along which energy is transmitted from the Energy Source Node  $s$  to the Target Node  $t$ . Each path is composed of segments of the vehicular routes.*

For each pair of  $(s, t)$ , we can construct the set of all possible paths  $\mathcal{P}(s, t)$ . Each path

<sup>3</sup>Delay  $d(a_i)$  can be considered as some average value and it is likely to be a constant when the surrounding traffic conditions do not change. This delay can be easily relaxed to be a time-varying parameter as part of the future work.

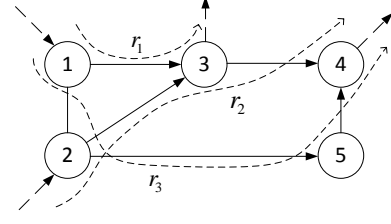


Fig. 1. Energy paths.

$p_j(s, t) \in \mathcal{P}(s, t)$  can be represented by  $p_j(s, t) = \langle r_1^j(n_1, m_1), \dots, r_i^j(n_i, m_i), \dots, r_{|p_j|}^j(n_{|p_j|}, m_{|p_j|}) \rangle$ , where  $r_i^j(n_i, m_i)$  refers to the  $i$ -th segment of  $p_j$ , and it is the sub-route of  $r_i^j$  with the starting arc  $n_i$  and the ending arc  $m_i$ .  $|p_j|$  is the number of sub-routes used to construct  $p_j$ .  $p_j(s, t)$  also needs to satisfy (i)  $tail(r_1^j(n_1)) = s$ , (ii)  $head(r_{|p_j|}^j(m_{|p_j|})) = t$ , and (iii)  $head(r_i^j(m_i)) = tail(r_{i+1}^j(n_{i+1}))$ , for  $i = 1, 2, \dots, |p_j| - 1$ . Consider the example given in Fig. 1, which contains a subgraph of  $\mathcal{G}$ . There are three vehicular routes,  $r_1$ ,  $r_2$ , and  $r_3$ , and each passes through some of the nodes in the subgraph. Specifically,  $r_1$  passes through Nodes 1 and 3;  $r_2$  passes through Nodes 2, 3, and 4; and  $r_3$  passes through Nodes 1, 2, 5, and 4. Suppose that we decide to transmit energy from Nodes 1 to 4. There are three energy paths in  $\mathcal{P}(1, 4) = \{p_1(1, 4), p_2(1, 4), p_3(1, 4)\}$ .  $p_1(1, 4) = \langle (1, 3), (3, 4) \rangle$  is constructed from two vehicular routes, where  $(1, 3)$  and  $(3, 4)$  come from  $r_1$  and  $r_2$ , respectively. Hence, we have  $p_1(1, 4) = \langle r_1^1((1, 3)), r_2^1((3, 4)) \rangle$ .  $p_2(1, 4) = \langle (1, 2), (2, 3), (3, 4) \rangle$  is constructed from  $r_3$  and  $r_2$ . We have  $p_2(1, 4) = \langle r_3^2((1, 2)), r_2^2((2, 3), (3, 4)) \rangle$ . Similarly,  $p_3(1, 4) = \langle (1, 2), (2, 5), (5, 4) \rangle$  is constructed from  $r_3$  only. Hence, we have  $p_3 = \langle r_3^3((1, 2), (5, 4)) \rangle$ .

At the (dis)charging facilities, energy can be transferred wirelessly from and to the vehicles on the move. We assume that each energy transfer takes a negligible time and it takes time  $d(p_j)$  units for a vehicle to “propagate” along  $p_j$ , where

$$d(p_j) = \sum_{i=1}^{|p_j|} d(r_i^j(n_i, m_i)) = \sum_{i=1}^{|p_j|} \sum_{a_k \in r_i^j(n_i, m_i)} d(a_k). \quad (1)$$

We standardize the maximum amount of energy that can be carried by each EV in each charging-discharging cycle, i.e., the “packet size”, denoted by  $w$  units. Let  $f_i^j$  be the traffic flow of the  $i$ -th segment of  $p_j$ . By assigning some EVs along the sub-routes to carry energy, the energy transfer rate of  $p_j$ , denoted by  $g_j$  units, satisfies:

$$g_j \leq w f_i^j, \quad i = 1, \dots, |p_j|. \quad (2)$$

#### D. Charging-Discharging Cycle

There is energy loss in both of the dynamic charging and discharging processes. The energy efficiencies of charging and discharging are given by  $z_c$  and  $z_d$ , respectively, and thus, the fractions of  $(1 - z_c)$  and  $(1 - z_d)$  correspond to the portions of energy lost in charging and discharging, respectively. When a

vehicle is employed to carry energy, there exists a charging-discharging cycle along each sub-route. For example, in Fig. 1, when we decide to transport some energy from Nodes 1 to 3, we can charge a vehicle along  $r_1$  at Node 1 and then discharge at Node 3. Let  $z = z_c z_d$ . Hence, at the end of each charging-discharging cycle, we can only retain a fraction  $z$  of energy.

If we know the designated routes of all EVs, we can make use of the EVs to transmit energy more than one hop in  $\mathcal{G}$  without discharging. Otherwise, they need to be discharged and re-charged at each node (i.e., the charging-discharging cycle takes place at each hop). With the support of VANET, most vehicles are connected. Without loss of generality, the participating EVs are obligated to report (part of) their travel plans. In this way, for each route  $r_i$ , we can tell which EVs are traveling along the route. Suppose that we know the routes of all EVs. If  $x$  units of energy are required to reach the destination of the energy path  $p_j$ , which is composed of  $|p_j|$  sub-routes, we need to transmit  $\frac{x}{z^{|p_j|}}$  units of energy at the source of  $p_j$ . On the other hand, this incurs energy loss equal to  $(\frac{1}{z^{|p_j|}} - 1)x$  units. The amount of time required to transport energy is composed of the total “propagation delay” and “transmission delay” along the transmission path. To transport  $\frac{x}{z^{|p_j|}}$  units of energy along  $p_j$  from its source, it takes a duration of  $d(p_j) + \frac{x}{z^{|p_j|}g_j}$  units (see (1)). In other words, in the time window  $T$ , the amount of energy transferable along  $p_j$ , denoted by  $x_j$  units, is governed by  $x_j \leq (T - d(p_j))z^{|p_j|}g_j$ , and the corresponding energy loss incurred is  $(\frac{1}{z^{|p_j|}} - 1)x_j$  units. Therefore, the amount  $x(s, t)$  units of energy transferred to Node  $t$  from Node  $s$  in a time period  $T$  satisfies:

$$x(s, t) = \sum_{j|p_j \in \mathcal{P}(s, t)} x_j \leq \sum_{j|p_j \in \mathcal{P}(s, t)} (T - d(p_j))z^{|p_j|}g_j \quad (3)$$

The corresponding amount of energy loss of  $L(s, t)$  units is given by:

$$L(s, t) = \sum_{j|p_j \in \mathcal{P}(s, t)} (\frac{1}{z^{|p_j|}} - 1)x_j. \quad (4)$$

#### IV. PROBLEM FORMULATION

In this section, we study two possible practical problems based on the model developed in the previous section. We will formulate the problems in the form of optimization and give some analytical results.

A small packet size  $w$  is sufficient to facilitate a noticeably large amount of energy transfer over a large geographical area and this will be verified in Section V. Since a practical value of  $w$  is very small when compared with the battery capacity of typical EVs, for a single-battery EV, only a small portion of the battery will be reserved for VEN while the rest can still be used to support the normal EV operations. In this way, we can simply assume that an EV can serve multiple energy paths simultaneously. In this section, we systemically study how energy should be transmitted over multiple energy paths in two perspectives, i.e., the transferable amount of energy and the energy loss.

We first study how to convey energy over the energy paths by maximizing the total amount of transferred energy subject to a maximum tolerable energy loss. Given the source-destination pair  $(s, t)$ , we can determine the set of energy paths

$\mathcal{P}(s, t)$  based on the method discussed in [30]. Suppose that we have an energy loss requirement with an upper limit  $\bar{L}$ . Based on Section III, we formulate the problem as follows:

##### Problem 1.

$$\begin{aligned} & \text{maximize} && \sum_{j=1}^{|\mathcal{P}(s, t)|} x_j \end{aligned} \quad (5a)$$

$$\text{subject to} \quad x_j \leq (T - d(p_j))z^{|p_j|}g_j, \quad j = 1, \dots, |\mathcal{P}(s, t)|, \quad (5b)$$

$$g_j \leq wf_i^j, \quad i = 1, \dots, |p_j|, j = 1, \dots, |\mathcal{P}(s, t)|, \quad (5c)$$

$$\sum_{j=1}^{|\mathcal{P}(s, t)|} (\frac{1}{z^{|p_j|}} - 1)x_j \leq \bar{L} \quad (5d)$$

$$x_j \geq 0, \quad j = 1, \dots, |\mathcal{P}(s, t)|. \quad (5e)$$

We maximize the total energy transferred in (5a), subject to the constraint of transferred amount on each path (5b), the energy transfer rate constraint (5c), the energy loss constraint (5d), and the non-negativity constraint (5e). Given  $\mathcal{P}(s, t)$  based on [30],  $|\mathcal{P}(s, t)|$ ,  $d(p_j)$ 's and  $|p_j|$ 's are constants.  $z$ ,  $w$ ,  $T$ ,  $f_i^j$ 's, and  $\bar{L}$  are system parameters while  $x_j$ 's and  $g_j$ 's are variables. We can see that Problem 1 is indeed a linear program (LP) and the solution can be easily computed with a standard LP solver.

In some cases, we may just need to convey a given amount of energy and retain the flexibility to the energy loss. We can minimize the total energy loss incurred provided that a given minimum energy amount  $\underline{X}$  can be achieved. We formulate the problem in the following:

##### Problem 2.

$$\begin{aligned} & \text{minimize} && \sum_{j=1}^{|\mathcal{P}(s, t)|} (\frac{1}{z^{|p_j|}} - 1)x_j \end{aligned} \quad (6a)$$

$$\text{subject to} \quad x_j \leq (T - d(p_j))z^{|p_j|}g_j, \quad j = 1, \dots, |\mathcal{P}(s, t)| \quad (6b)$$

$$g_j \leq wf_i^j, \quad i = 1, \dots, |p_j|, j = 1, \dots, |\mathcal{P}(s, t)| \quad (6c)$$

$$\sum_{j=1}^{|\mathcal{P}(s, t)|} x_j \geq \underline{X} \quad (6d)$$

$$x_j \geq 0, \quad j = 1, \dots, |\mathcal{P}(s, t)|. \quad (6e)$$

We minimize the total energy loss in (6a), subject to the energy transfer constraint (6d) and some similar constraints as in Problem 1, where  $\underline{X}$  is a system parameter. Similar to Problem 1, Problem 2 is also an LP and the solution can be easily determined. Note that we aim to introduce the framework for VEN in this paper and the routing is studied in [30]. As the problems are relatively easy to solve, instead of showing how the problems are solved with numerical examples, we give some analytical results below to obtain more insights:

**Theorem 1.** Suppose

$$z^{|p_j|} \leq \frac{1}{2}, j = 1, \dots, |\mathcal{P}(s, t)|. \quad (7)$$

To achieve the maximum transferable energy, the tolerant energy loss  $\bar{L}$  should be set sufficiently large. Similarly, to achieve the minimum tolerable energy loss, the required transferable amount of energy  $\underline{X}$  should be set sufficiently small.

*Proof:* By introducing a dummy variable  $\underline{X}$ , we can re-write Problem 1 as

**Problem 3.**

$$\text{maximize } \underline{X} \quad (8a)$$

$$\text{subject to } x_j \leq (T - d(p_j))z^{|p_j|}g_j, \quad j = 1, \dots, |\mathcal{P}(s, t)|, \quad (8b)$$

$$g_j \leq wf_i^j, \quad i = 1, \dots, |p_j|, j = 1, \dots, |\mathcal{P}(s, t)|, \quad (8c)$$

$$\sum_{j=1}^{|\mathcal{P}(s, t)|} x_j \geq \underline{X} \quad (8d)$$

$$\sum_{j=1}^{|\mathcal{P}(s, t)|} \left(\frac{1}{z^{|p_j|}} - 1\right)x_j \leq \bar{L} \quad (8e)$$

$$x_j \geq 0, \quad j = 1, \dots, |\mathcal{P}(s, t)|. \quad (8f)$$

By introducing a dummy variable  $\bar{L}$ , we can re-write Problem 2 as

**Problem 4.**

$$\text{minimize } \bar{L} \quad (9a)$$

$$\text{subject to } x_j \leq (T - d(p_j))z^{|p_j|}g_j, \quad j = 1, \dots, |\mathcal{P}(s, t)| \quad (9b)$$

$$g_j \leq wf_i^j, \quad i = 1, \dots, |p_j|, j = 1, \dots, |\mathcal{P}(s, t)| \quad (9c)$$

$$\sum_{j=1}^{|\mathcal{P}(s, t)|} x_j \geq \underline{X} \quad (9d)$$

$$\sum_{j=1}^{|\mathcal{P}(s, t)|} \left(\frac{1}{z^{|p_j|}} - 1\right)x_j \leq \bar{L} \quad (9e)$$

$$x_j \geq 0, \quad j = 1, \dots, |\mathcal{P}(s, t)|. \quad (9f)$$

Hence, both Problem 3 and Problem 4 share the same feasible region, denoted by  $\mathcal{C}$ . Let  $x = [x_1, \dots, x_{|\mathcal{P}(s, t)|}]^T$ . Then we have

$$\begin{aligned} \underline{X} &\leq \sup\{\underline{X} | x \in \mathcal{C}\} \\ &\leq \sum_{j=1}^{|\mathcal{P}(s, t)|} x_j \\ &\leq \sum_{j=1}^{|\mathcal{P}(s, t)|} \left(\frac{1}{z^{|p_j|}} - 1\right)x_j \\ &\leq \inf\{\bar{L} | x \in \mathcal{C}\} \\ &\leq \bar{L}. \end{aligned}$$

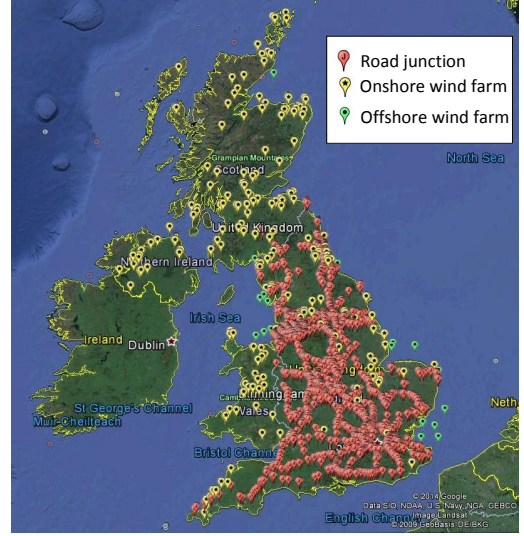


Fig. 2. Locations of road junctions, and onshore and offshore wind farms (adopted from Google Earth).

Hence, for Problem 3, too small an  $\bar{L}$  can result in  $\underline{X} \leq \bar{L} \leq \sup\{\underline{X} | x \in \mathcal{C}\}$  such that  $\underline{X}$  cannot achieve its maximum value. Similarly, for Problem 4, too large an  $\underline{X}$  can result in  $\inf\{\bar{L} | x \in \mathcal{C}\} \leq \underline{X} \leq \bar{L}$  such that  $\bar{L}$  cannot achieve its minimum value. ■

Theorem 1 is useful when we need to optimize the total transferred energy and energy loss simultaneously. Condition (7) is met when the energy efficiency  $z$  is low or the energy paths are composed of many vehicular sub-routes. The latter may be due to the source and destination being too far apart or limited vehicular routing information.

## V. PERFORMANCE EVALUATION

In this section, we demonstrate that a significant amount of energy can be transmitted through VEN in a reasonable period of time. We illustrate this by transmitting the renewable energy produced from the wind farms located in remote areas of the United Kingdom (U.K.) to the city of London.

We construct a VEN by adopting the existing U.K. road networks. Based on [31], we create the network with 998 nodes and 2470 arcs ( $a_i$ 's). We adopt one set of real traffic data acquired in June 2013 to specify the journey time, distance, and vehicular flow for each of the road segments (i.e., arcs). We randomly create 4788 vehicular routes ( $r_i$ 's) in the road network, each of which is composed of several connected road segments no longer than 200 km. The traffic flow and total journey time of each  $r_i$  are set with the minimum of vehicular flows of the corresponding composite  $a_i$ 's and the sum of individual journey times of the composite  $a_i$ 's, respectively.

U.K. is the sixth largest nations producing wind energy, with an annual energy production of more than  $26 \times 10^6$  MWh [32], but only 26% was brought online in 2013 [33]. According to [34] and [35], there are 203 onshore and 20 offshore wind farms. Fig. 2 shows the locations of the road junctions and the wind farms. We select 67 nodes in the the road network, which are close to the wind farms, as the energy sources ( $s$ 's)

TABLE I  
SPECIFICATIONS OF SOME POPULAR ELECTRIC CARS IN THE MARKET

Model	Range per charge (km)	Battery capacity (kWh)	Ref.
Tesla Model S	373–484	85	[20], [36]
Nissan Leaf	117	24	[19], [36]
BMW i3	129–161	18.8	[17], [36]
Tesla Roadster	356–394	53	[21], [36]
Toyota RAV4 EV	166	27.4	[22], [36]
Honda Fit EV	132–212	20	[18], [36]

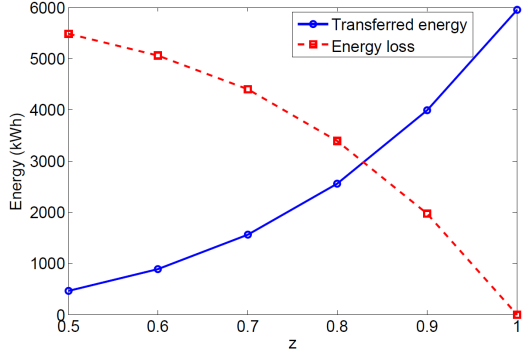


Fig. 3. Transferred energy and energy loss at different efficiencies.

in VEN. We select one junction near London as the energy destination  $t$  for demonstrative purpose. Energy paths  $p_j(s, t)$ 's are constructed by augmenting sub-routes of the 4788  $r_i$ 's. Energy is transmitted from the sources to the destination along some of the energy paths.

Consider the nominal setting of 0.1% EV penetration rate,<sup>4</sup> packet size  $w$  of 0.1 kWh, efficiency rate  $z$  of 0.9<sup>5</sup>, and time period  $T$  of 5 hours. Table I gives the specifications of some popular EVs available in the market, showing that our energy packet size is rather conservative. In the following, we study the total transferred energy (reaching London from the wind farms) and the corresponding energy loss by varying one parameter in each case. Each data point is computed from the right-hand side of either (3) or (4), in which, for simplicity, only some paths are considered instead of all possible energy paths.

Fig. 3 shows the impact of total transferred energy and energy loss by changing  $z$  from the nominal setting. In five hours, the amounts of energy transferred are in the order of MWh. Note that the allowed period has already included the time required for the EVs to move from one place to another. The more efficient the wireless energy transfer technology, the more energy can be transferred with smaller energy loss. When  $z$  is smaller than 0.83,<sup>6</sup> the amount of energy loss can overshoot the transferred energy. Hence  $z$  is an important factor when we design VEN. However, if there is no VEN or other similar energy transmission architecture available, the

<sup>4</sup>The EV penetration rate refers to the percentage of participating EVs in the vehicle population. When the EV penetration rate is 0.1%, one out of 1000 cars supports VEN.

<sup>5</sup>The industry expects the efficiency of wireless energy transfer on moving vehicles can exceed 90% [37]. NASA has developed a prototype called EVWireless with over 90% energy efficiency [38].

<sup>6</sup>This threshold actually depends on the energy paths chosen for energy transmission.

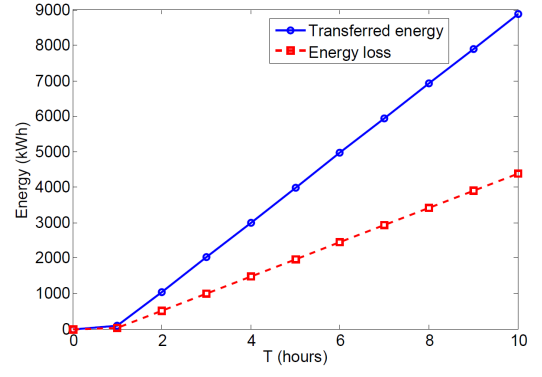


Fig. 4. Transferred energy and energy loss in various periods of time.

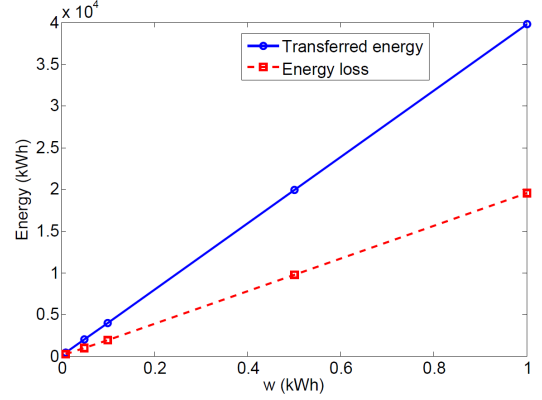


Fig. 5. Transferred energy and energy loss with various buffer sizes.

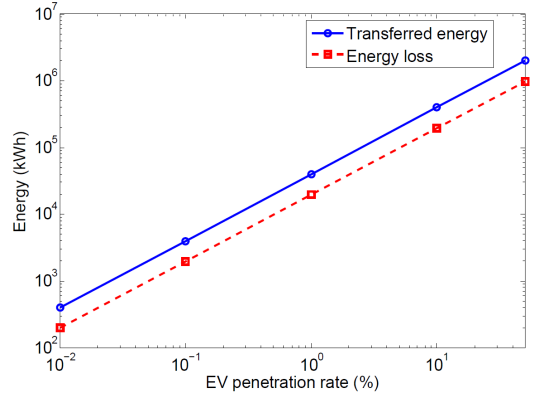


Fig. 6. Transferred energy and energy loss with different EV penetration rates.

huge amount of renewable energy may need to be stored at the original generation locations and eventually wasted due to surplus renewable production. As technology of wireless energy transfer keeps advancing, the overall efficiency will improve. Fig. 4 studies the impact of the allowed time period. With  $T \leq 1$  hour, the transferred energy is very small as most of the EVs carrying the energy have not reached the destination. With larger  $T$ , more transferred energy and energy loss occur. The gap between transferred energy and energy loss grows with  $T$  showing that the energy transfer is more efficient in a longer time period. Fig. 5 illustrates the impact



of the packet size. More energy will reach the destination and more energy is also lost when a larger amount of energy can be (dis)charged each time. A larger packet size leads to a higher efficiency as more energy can be transmitted than lost. Finally, Fig. 6 shows that the transferred energy and energy loss grow linearly with the EV penetration rate.

To summarize, we set up a VEN to transport renewable energy from remote wind farms to London. Note that the total transferable energy and loss shown above are not optimal, as we have just selected *some* of the energy paths to transport the energy. In fact, there may be shorter paths experiencing fewer charging-discharging cycles. Nevertheless, the amount of energy transferable through VEN in our illustration is still very significant. Although there is energy loss in VEN, most of the energy to be transported in VEN would be eventually lost in the case without VEN. This shows that VEN can complement the power network and enhance the overall power transmission rate.

## VI. POTENTIAL EXTENSIONS

In this paper, we introduce VEN and show its capability. Below we give some potential extensions of VEN worth further investigations.

1) *Effective Energy Transfer*: In our setting of the model, we have assumed that each node in  $\mathcal{G}$  is equipped with a small energy storage. With enhanced storage, nodes can act as big energy reservoirs. We may accumulate energy at some nodes, and we can make the energy transfer rate larger when there are more EVs passing through (especially when the traffic conditions are changing). This allows us to have better control of the whole energy transfer process.

2) *Multi-source Multi-destination Routing*: With the energy packet-switching design, VEN shares many similarities with the packet-switched data communication network, and thus, many ideas and techniques originally designed for the data network may be applied to VEN. In most cases, there exist multiple energy sources and destinations. The matching between the sources and destinations and the connections between them need to be carefully designed.

3) *Impact of Predictable Vehicular Routes*: Depending on VANET and other system settings, we may possess different information of the intended routes of the participating EVs. The levels of details of the vehicular routing information affect the number of charging-discharging cycles required. For example, we can rely on vehicles without routing information to transport for one hop only.<sup>7</sup> We can make use of those EVs with a longer known route to carry energy further away. The levels of details of predictable vehicular routes impact the system performance.

## VII. CONCLUSION

The smart grid introduces many new elements which are not easily incorporated into the existing power system due to power reliability and security reasons. Many novel and interesting smart grid implementations rely on the power network

to convey power and they can be more easily realized if there exists an independent infrastructure for power transmission without interference to the existing power network. In this paper, we introduce VEN, which is capable of transporting energy across a large geographical area with EVs. VEN is built upon the traffic network and it relies on existing well-developed technologies. Small amounts of energy, as energy packets, are carried by EVs through multiple vehicular routes. By carefully designing the energy packet routing, we can transport energy from energy sources to destinations. In this paper, we give a thorough preliminary study of VEN and discuss its characteristics and possible drawbacks. We demonstrate its significance by setting up a VEN with real road traffic data in the U.K. and show that a considerable amount of renewable energy can be transported from some remote wind farms to London under some reasonable assumptions. For the cases with the renewables, if there is no VEN or other similar energy transmission architecture available, the huge amount of renewable energy may need to be stored at the original generation locations and eventually wasted due to surplus renewable production. As most employed equipment is built upon off-the-shelf technologies, we can realize VEN by designing appropriate coordinating protocols. It is shown that VEN can complement the power network and enhance the overall power system performance. In this work, we do not intend to posit VEN as a perfect solution for energy transmission. Instead, we may consider VEN as a feasible design to complement the power network and enhance the overall power system performance. We summarize our contributions as: (1) design VEN as a realistic energy transmission platform incorporated with state-of-the-art technologies like VANET and dynamic charging; (2) propose a mathematically tractable framework for VEN allowing us quantify important variables like transferable energy, transmission rate, and energy loss; (3) formulate two practical problems and provide insightful analytical results; (4) demonstrate that VEN can sustain significant energy transmission over a large geographical region in real-world settings; and (5) provide a list of potential extensions for further development. With the energy packet-switching design, VEN has many potential future extensions by incorporating ideas and results from the packet-switched data network.

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<sup>7</sup>A vehicle which has gone onto a road segment must exit that segment.



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